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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Single-sided p^+n and double-sided silicon strip detectors exposed to fluences up to $2 \times 10^{14}/cm^2$ 24 GeV protons

L. Andricek[a], T. Gebhart[a], D. Hauff[a], J. Kemmer[b], E. Koffeman[a], G. Lutz[a], R.H. Richter[a], T. Rohe[a], R. Wunstori[c]

[a]*Max-Planck-Institut für Physik, München, Germany*
[b]*KETEK GmbH, Oberschleissheim, Germany*
[c]*Universität Dortmund, Dortmund, Germany*

Presented by G. Lutz

MPI-Halbleiterlabor, Paul-Gerhardt-Allee 42, 81245 München, Germany

Abstract

Single-sided p^+n and double-sided detectors have been designed for surviving the drastic changes of material properties expected from their use in the harsh radiation environment at the LHC. Detectors optimized for capacitive charge division readout have been exposed to a fluence of $2 \times 10^{14}/cm^2$ 24 GeV protons. Their principal design characteristics and properties after irradiation are described. An explanation for the hitherto not understood survival of single-sided p^+n detectors is given. First results with single-sided p^+n detectors optimized for binary readout are presented.

1. Introduction

The development of semiconductor detectors for the environment at the future Large Hadron Collider (LHC) at CERN poses severe challenges. This is due to the radiation-induced drastic changes in the detector material properties. In addition, high-speed operation and low-cost production are required. Single- and double-sided silicon strip detectors have been designed and produced in the Max-Planck Semiconductor Laboratory at Munich. In the framework of the ATLAS irradiation test program they were exposed at the CERN Proton Synchrotron (PS) to an irradiation of $2 \times 10^{14}/cm^2$ 24 GeV protons.

The detector concepts and the performance in the irradiation test are described. Static *I–V* and *C–V* measurements give information on high-voltage operation capabilities and on the voltage needed for full depletion of the detectors. The irradiated single-sided structured p^+n detector shows a current–voltage characteristics very similar to that of the double-sided detectors. Such a behaviour is naively not expected. A mechanism for the

* Corresponding author.

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limitation of currents generated in the cut region is proposed.

Measurements with a radioactive source allow the investigation of charge collection properties, and in particular, a comparison of the relative merits of n-side and p-side readout. At very high fluence an 'excess noise' is observed. It is due to the particular biassing circuit chosen. We give a tentative explanation for the noise mechanism, based on the creation on bulk traps.

Based on the results of the irradiation test single-sided p^+n detectors optimized for binary electronics have been designed and produced. First results of unirradiated detectors are presented.

2. Effects of irradiation – challenges

Exposing detectors to the radiation environment at LHC will induce bulk defects with concentrations exceeding by far those of the original dopants. In addition oxide and Si–SiO_2 interface damage leads to an order of magnitude increase of the oxide charge.

The well-known consequences of the bulk material changes [1] are: (a) increase of detector leakage current; (b) change of effective doping from n to p-type (type inversion) followed by a steady increase of full depletion voltage; this is enhanced by 'reverse annealing', the further very slow increase of effective p-doping even after the end of the radiation exposure; (c) charge trapping (signal loss).

Less well known is the low conductivity of the undepleted bulk material found by Li [2] and which can be explained by the creation of near-mid-gap acceptor-type defects [3]. It gives a key for understanding the survival of single-sided p^+n detectors after type inversion.

The increase of oxide charge can lead to locally enhanced electric field strengths and, as a consequence, to electric breakthrough and micro discharges.

The detectors designed for LHC operation will have to function properly despite the drastic radiation-induced material property changes. In addition they should: (a) be tolerant to local defects in the production process; (b) allow potential individual problems to be spotted before irradiation; (c) require a simple technology so that they can be produced at low cost.

3. Detectors for analog readout

Double-sided and single-sided structured p^+n detectors have been produced in the MPI semiconductor laboratory. Three double-sided and one single-sided detector were irradiated and their properties after irradiation tested.

3.1. Detector design

The detectors have been designed for analog readout making use of capacitive charge division. Capacitively coupled readout with punch through

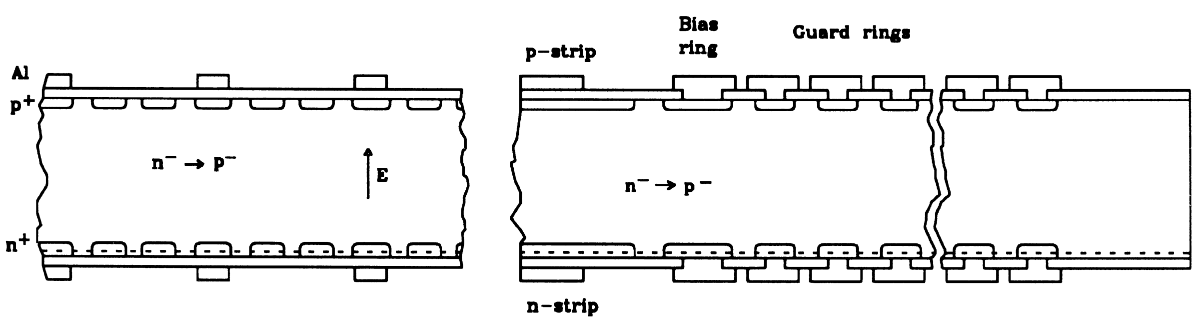

Fig. 1. Principal design characteristics of the double-sided strip detector: cross-section perpendicular to the strip direction (left) and along the strip direction across the multi-guard ring breakdown protection structure towards the cutting edge (right). As indicated, the effective bulk doping changes from n^- to p^- during irradiation.

biasing has been chosen, the latter option motivated by reasons of simplicity and cost reduction.

The cross-section through a double-sided strip detector, both across and along the strips (Fig. 1) shows the principal design characteristics. The wide strip – narrow gap topology results in reduced sensitivity to oxide charge buildup due to the reduction in lateral electric fields and potential drop on the semiconductor surface especially on the n-side of the detector [4]. The two floating strips inbetween readout strips have been chosen as a compromise between the conflicting requirements of enhanced charge division, optimal charge collection and electronic noise which is dependant on the capacitive load. The readout pitch on both sides of the detectors is 112.5 μm, the detector size $6 \times 6\,cm^2$. Strips on the n-side are rotated by 40 mrad with respect to the p-side. Insulation between n-strips is accomplished by an unstructured large area medium dose p-implantation ('spray implant') which at the strip locations is overcompensated by the n^+-strip implants. This, in addition to the simplification of technology, has the important properties of: (a) tolerance to photolithographic errors as – in contrast to insulation by strongly doped p-stops in other designs – nowhere highly doped n- and p-regions can touch each other; (b) irradiation reduces the electric field strength on the n-side [4], so that possible problems of breakdown can be spotted before irradiation. Breakdown protection structures [5] are present on both sides of the detector and are rather similar in structure and functioning.

Single-sided p^+n detectors are of exactly the same design as the p-side of the double-sided detector, the backside being a large area n^+ implant.

Detectors have been produced with a rather simple fault tolerant technology using double-layer Si_3N_4 on SiO_2 dielectric to achieve a very high coupling capacitor yield. For the double-sided detectors only eight and for the single-sided detectors four photolithographic steps were used in producing a detector.

3.2. Irradiation of double- and single-sided p^+n detectors

An irradiation with 24 GeV protons in the CERN PS up to a fluence of $2 \times 10^{14}/cm^2$ has been done in the framework of the ATLAS irradiation test program. Detectors were biassed at 150 V during the irradiation. Measurements of *I–V* characteristics were performed several times during and after irrradiation. The *C–V* characteristics after full irradiation allow the determination of the full depletion voltage.

Of particular interest (due to the potential of using simple and cost-effective detectors) is the behaviour of single-sided p^+n detectors after type inversion. Their radiation hardness was in doubt due to the missing explanation for a mechanism preventing catastrophic breakdown at detector rim after type inversion.

3.2.1. I–V characteristics of irradiated detectors

Having bias and inner guard ring separated, volume and edge generated currents can be measured independently. All detectors show stable operation up to high bias voltage. They all have low 'edge generated' currents and the saturating volume generated current agrees with expectation from bulk damage.

As an example, results from the irradiated single-sided p^+n detector are shown in Figs. 2 and 3. Below 520 V bias the edge generated current contributes less than 10% to the total leakage current. The current from the strip region scales with temperature as expected for the volume generated current.

3.2.2. Full depletion voltage

From measurement of the *C–V* characteristics, the full depletion voltage can be determined. For strongly irradiated detectors (above the type inversion fluence) this measurement has to be done at very low frequency due to the near intrinsic resistivity of the undepleted bulk region.

A strongly different shape of $1/C^2$ versus bias voltage is observed for irradiated and unirradiated detectors (Fig. 4). The difference in shape of the *C–V* relationship after type inversion was already observed at the time of discovery of type inversion [1]. In this reference it was also shown, by comparison with source signal measurements, that the saturation point in the *C–V* measurement still gives the correct full depletion voltage.

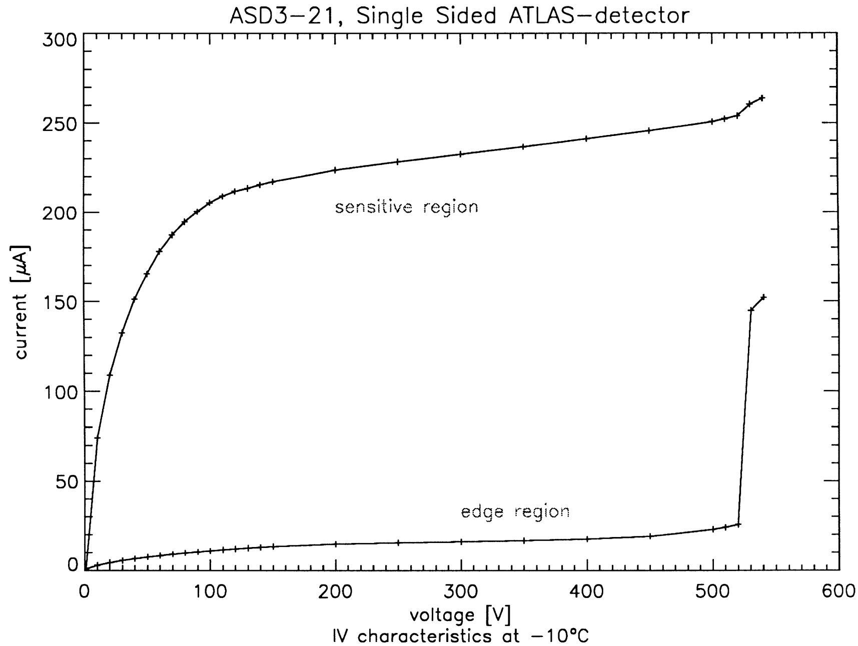

Fig. 2. Volume and edge generated leakage currents measured at -10°C.

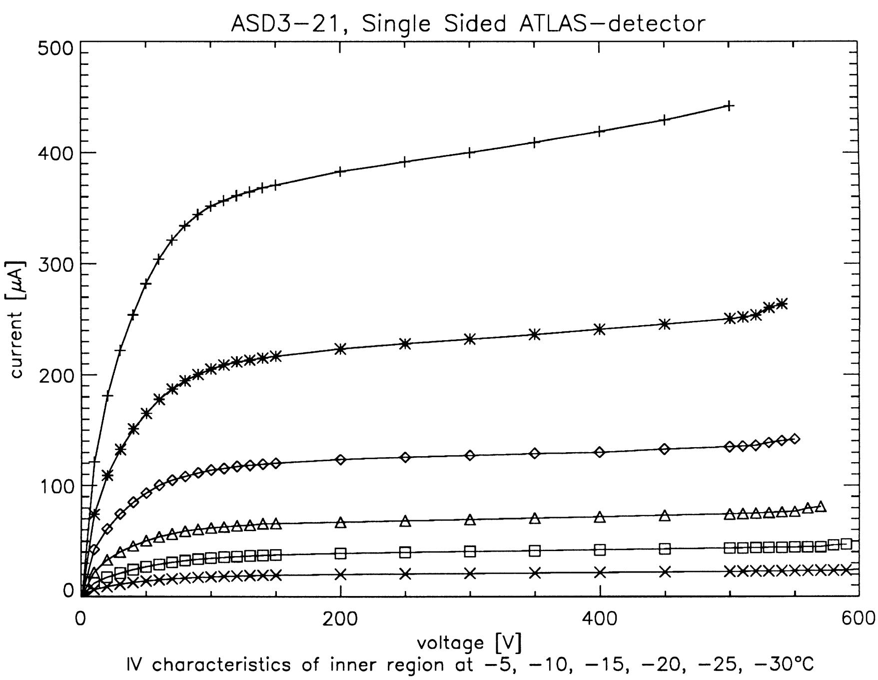

Fig. 3. Volume generated leakage current measured at various temperatures (-5, -10, -15, -20, -25, -30°C from top to bottom).

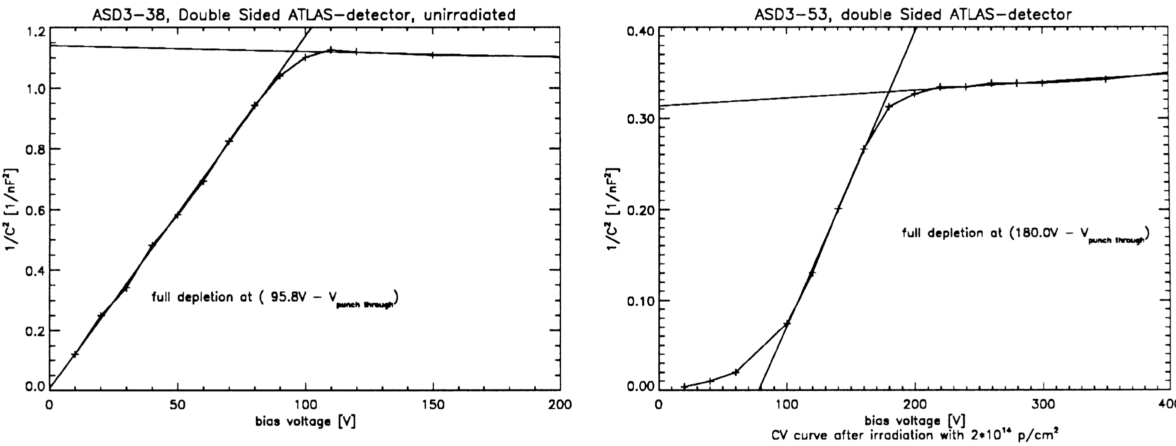

Fig. 4. Double-sided unirradiated and irradiated detector. From the $1/C^2$ distribution full depletion voltages of 95 and 180 V have been found.

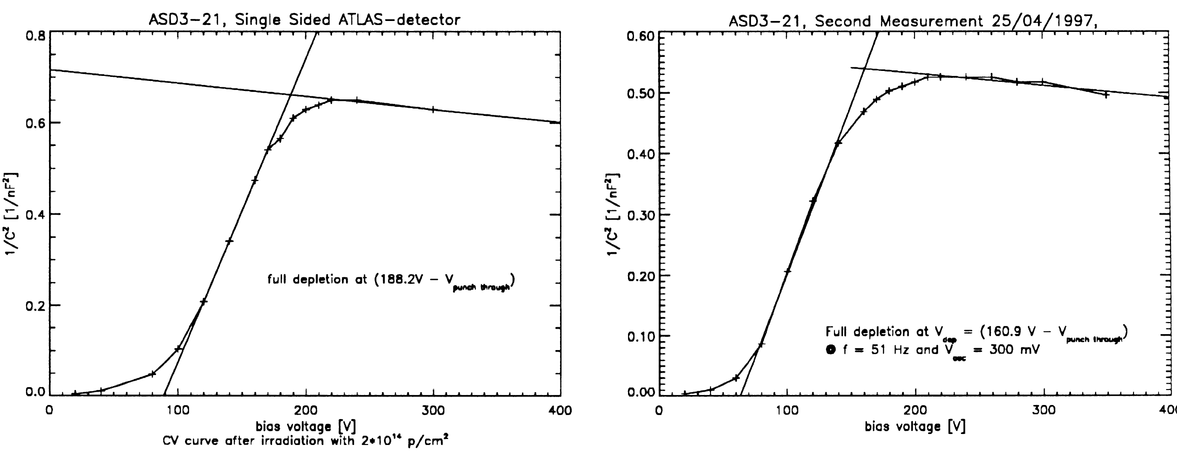

Fig. 5. The irradiated p^+n single-sided irradiated detector measured twice; before and after a 65 h warmup period to room temperature. A drop of the full depletion voltage from 188 to 161 V is extracted.

After irradiation the full depletion voltage initially decreases (dominant beneficial annealing) and then rises again (dominant reverse annealing). The detector is still in the first stage as can be seen in Fig. 5 where the measurements before and after a 65 h warmup period show a decrease of 27 V in the full depletion voltage.

3.3. Signal and noise measurements

The charge collection and noise properties of the irradiated detectors have been investigated using a radioactive source in exactly the same manner on both sides of a double-sided detector and a single-sided p^+n detector. The signals were read out subsequently with the identical unirradiated fast electronics chip, the FELIX [6]. The measurements were performed at $-17^{\circ}C$ (compare Section 5).

The signals are reconstructed forming a cluster consisting of the total charge in a maximum of five consecutive strips. Such a cluster is accepted when it has a total charge of at least five sigma above the average noise of the particular channels. A Landau

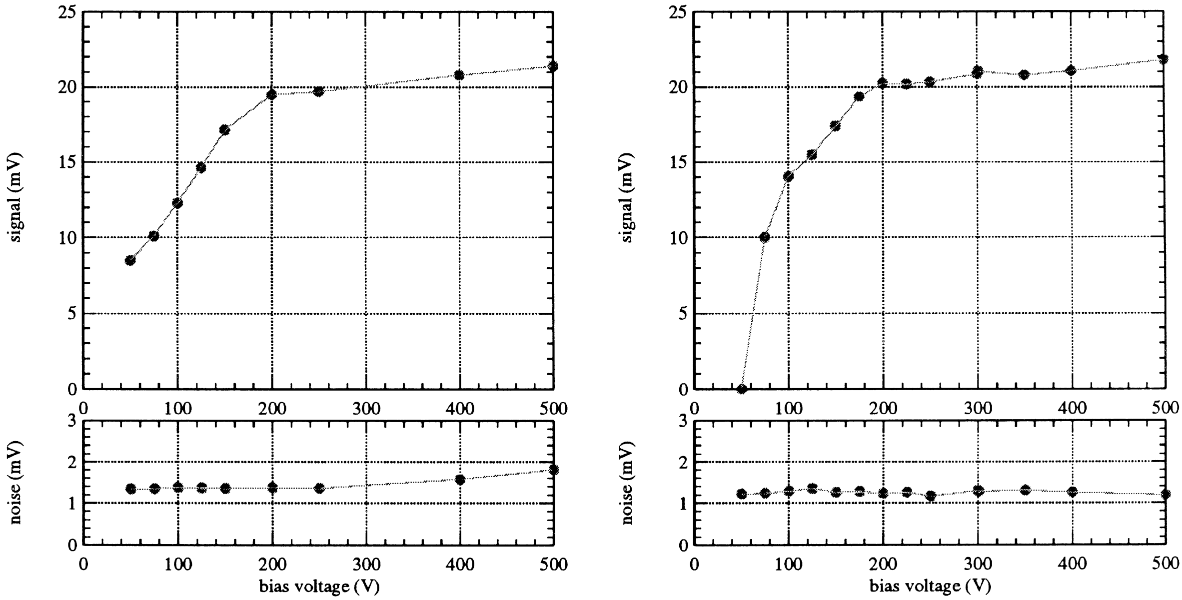

Fig. 6. The signals on both sides of the detector as a function of the applied bias voltage. Full signal is obtained at and above the depletion voltage of 180 V determined from C–V measurements. In the bottom part the average channel noise is shown.

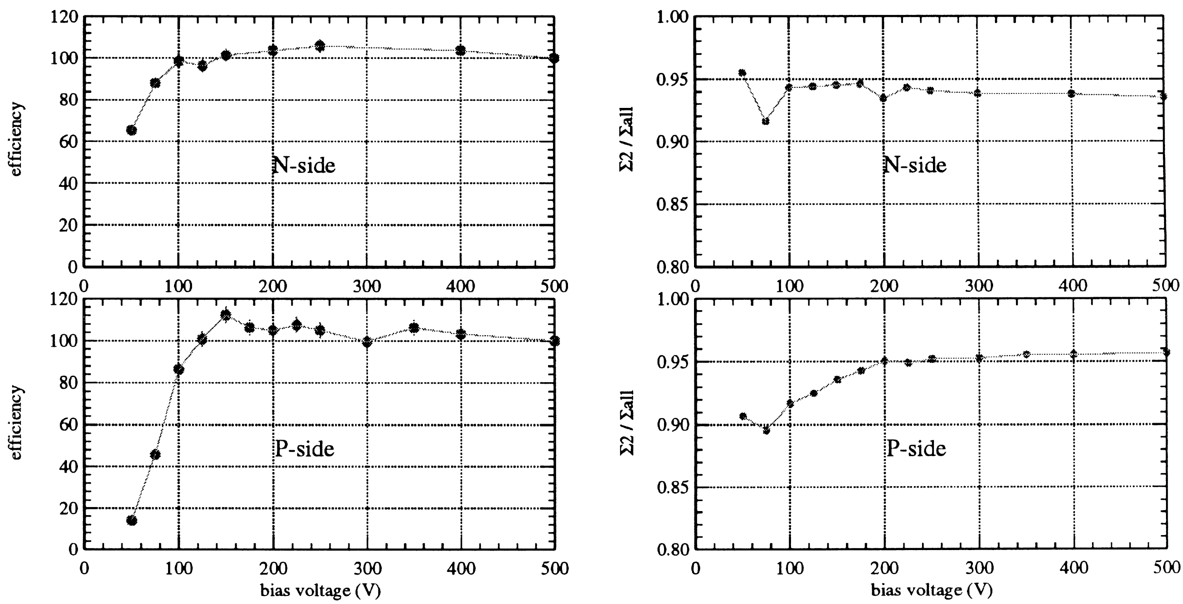

Fig. 7. The cluster finding efficiency (left) and the fraction of the total charge found in the two highest hits (right).

distribution (convoluted with a Gaussian) is fitted to the obtained pulse-height spectrum. The evolution of the signal on both sides of a double-sided irradiated detector as a function of the applied bias is shown in Fig. 6 together with the average channel noise.

A comparison for the efficiency of the two sides gives Fig. 7 in which the ratio of found clusters and source triggers, normalized to unity at 500 V bias is plotted.

To get an impression of the cluster size, the charge sum in the two highest channels in the cluster is compared with the total cluster charge in the right part of Fig. 7. Bear in mind that the charge spread over more than two strips is partially due to inclined tracks, however, this drops out in the comparison between the two sides.

We conclude that there are no gross differences in the readout of the two sides. The independence of noise on bias voltage is consistent with the perfect saturating shape of the current–voltage characteristics. Signal and noise measurements on the irradiated single-sided p^+n detector are consistent with the p-side of the double-sided detector.

4. Type-inversion survival of p^+n detectors

The main reason for the hesitation in using single-sided p^+n detectors in the high radiation level environment of e.g. the LHC, has been the missing explanation for their survival after type inversion. After type inversion the junction moves to the n^+ backside and with application of a reverse bias, the space charge region grows from this side touching the heavily damaged cut region. Thus a high leakage current was expected. In the following, a short simplified explanation for its limitation will be given, following the somewhat more explicit presentation in Ref. [7]. It is based on the high resistivity of the undepleted bulk region [2] due to the creation of near-mid-gap acceptor-type defect states [3].

Before type inversion (Fig. 8a) the space charge grows from top and the cutting edge is not reached. The situation after type inversion under the (unrealistic) assumption of absence of charge generation is shown in Fig. 8b. The electron layer below the positively charged oxide is connected to the n^+ layer at the bottom side by the conducting cut region. With increasing bias voltage the space charge region grows simultaneously from the bottom and the top, leaving an undepleted region 'connected' to the p^+ 'diode' in the center. When applying $V \approx V_{FD}/4$, a fully depleted potential valley is created in the rim region of the detector. This potential valley will be filled up from the side by holes created in the damaged cut region (Fig. 8c). However, the concentration of free holes, and therefore, also the conductivity in the valley are small in the electrically neutral filled valley region.[1] Thus, one arrives at a situation in which a resistive potential drop along the valley is observed. The current can be estimated from the high resistivity in the undepleted bulk. Such an estimate agrees reasonably well with the observed edge generated currents [7].

5. Biassing mechanism

Capacitively coupled readout requires the direct supply of the bias voltage to the strip implants. In the most straightforward way this is achieved by the implementation of polysilicon bias resistors. For reasons of technological simplicity and cost reduction punch through biasing [8] has been chosen. However, this choice has resulted in problems at very high irradiation fluences above approximately $10^{14}\,cm^{-2}$ 24 GeV protons. At temperatures above $-5°C$ and shaping times of 25 ns or larger a noticeable increase in noise with temperature is observed on the n-side as well as on the p-side.

An 'excess noise' had already been seen earlier in the CDF experiment [9]. Here a noise rising linearly with the shaping time and with the square root of the strip leakage current has been observed in irradiated detectors. However, no explanation for the effect was given.

A natural explanation for this scaling behaviour is given by the presence of a $1/f$ noise component in the punch through biasing circuit [10]. A very likely physical source for this noise component is

[1] An estimate for their density can be obtained from thermal equilibrium considerations (if defect properties and concentrations are known) leading to the Fermi level (and carrier concentrations) from the requirement of charge neutrality. More directly it can be extracted from resistance measurements of the undepleted bulk material. Both methods are not completely correct as the hole/electron ratio will strongly exceed the thermal equilibrium value.

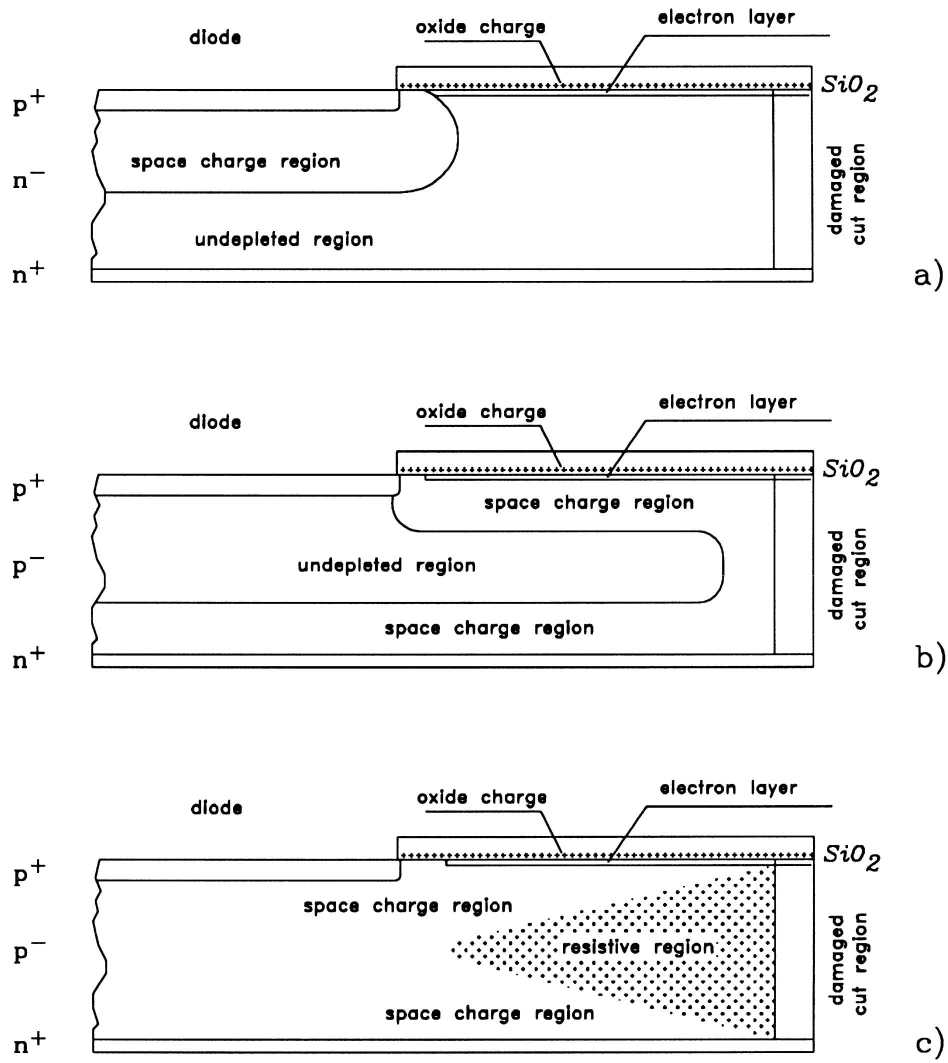

Fig. 8. Type inversion survival of single-side structured p^+n detectors: (a) the situation before type inversion; (b) after type inversion, without charge generation; (c) with charge generation in the cut region.

trapping of charge carriers in radiation generated bulk defects. These trapped charges modulate the barrier height of the punch through structure thus giving rise to superposition of random telegraph signals [11] in the bias current with varying characteristic times and amplitudes depending on type and position of the trap. Each of the traps produces a Lorentzian noise spectrum, their superposition is likely to lead to an approximative $1/f$ noise spectrum in the bias current.

That the excess noise observed in the CDF experiment is due to bulk damage and not a surface effect is supported by the absence of excess noise after γ-irradiation while it is present with proton irradiation [9].

The fact that excess noise is observed on both sides of our irradiated double-sided detectors in similar magnitude also supports the interpretation as bulk effect, since the oxide is shielded on the n-side by the p-spray implant, while it is bare on the p-side.

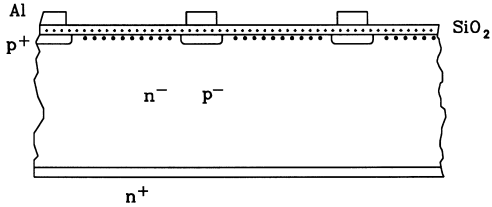

Fig. 9. Wide gap topology of p^+n binary detectors. The strip width (22 μm) is small with respect to the pitch (80 μm). All strips are read out. The effective bulk doping changes from n- to p-type after irradiation.

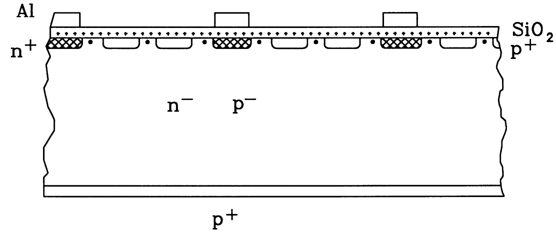

Fig. 10. n^+n binary detector with individual p-stop insulation. Each readout strip is surrounded by a electrically floating p-doped ring.

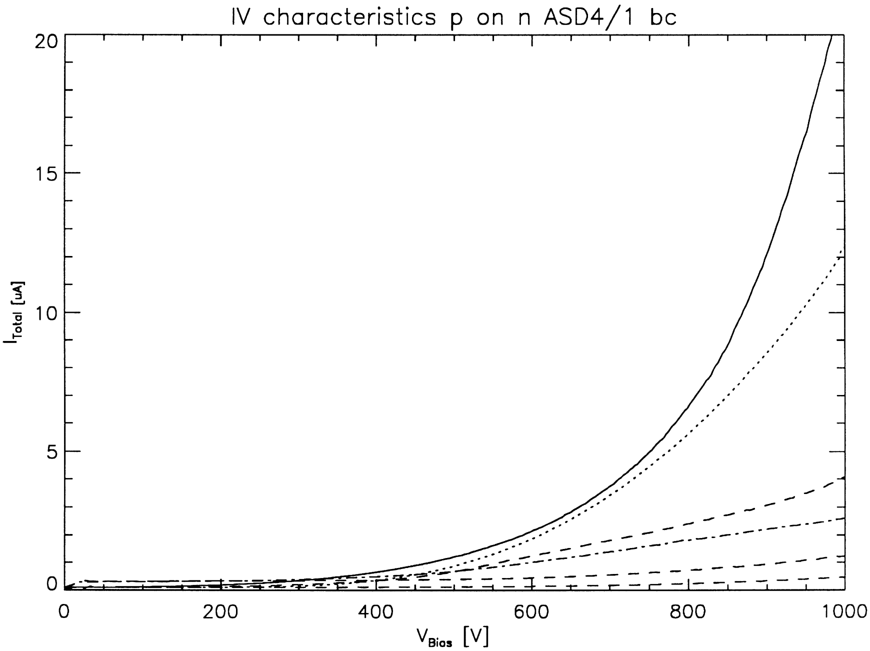

Fig. 11. Current–voltage characteristics of 5 binary readout prototype detectors measured at room temperature.

6. p^+n detectors for binary readout

Detectors for single-strip threshold binary readout have been optimized so as to suppress charge division as much as possible while minimizing the capacitive load to the amplifier by choosing a narrow-strip – wide-gap topology. In addition, the punch through biasing used in the analog readout detectors has been replaced by resistive biasing.

The chosen topology is shown in Fig. 9 and compared to a topology for n^+n detectors with strip insulation by individual p-type guard rings around each n-strip in Fig. 10.

Compared to n^+n readout the chosen topology offers the following important advantages: (a) no strip insulation measures are necessary as this occurs naturally by the positive oxide charge. Thus only one type of implantation is required on the strip side and the danger of joining high doped regions of different type due to photolithographic defects is avoided; (b) the low field region moves to the strip side after type inversion. Thus, the electric field at the strip side reduces with irradiation; (c) the potential in the gap region stays rather close to the strip voltage (it is shifted by approximately the flat band voltage with respect to the outer surface potential). This is in contrast to the wide-gap n^+n topology where the insulation structures drop to a very different potential from the strips after irradiation and therefore not only high fields but also higher bias voltages are required for full depletion; (d) the true single sided process leads to drastic simplification of the production.

Tests of unirradiated detectors show very satisfying results. Stable operation up to very high bias voltage has been observed in all tested detectors as shown in Fig. 11 and a very high strip yield 99.7% has been achieved. The detectors will be irradiated with 24 GeV protons at the CERN PS.

7. Summary – conclusions

Detectors tolerating the drastic radiation-induced material property changes induced in the LHC environment can be built. In particular, it is possible to build detectors which can be operated at very high bias voltages, both before and after irradiation. The use of double-sided detectors gave the possibility to compare charge collection properties on n- and p-side under exactly equal irradiation conditions. It was shown that the signals on the two sides vary in a very similar way with the applied bias voltage, only at very low bias the p-side signal is significantly lower. The fact that the noise does not significantly increase up to the highest applied bias voltage (500 V) shows the absence of problems as e.g. micro discharge, consistent with the perfect current voltage characteristics.

Likely mechanisms for the so far unexplained phenomena, the excess noise in the irradiated punch through biasing circuit and the type inversion survival of single-sided p^+n detectors have been proposed.

Double-sided detectors, offering (compared to single-sided detectors) the obvious advantages of reduced material and heat dissipation for the same amount of information, are well suited for applications in the LHC environment once the excess noise source in the punch through biasing circuit, becoming noticeable at very high fluences, is eliminated. This is easily accomplished by adopting resistive biasing.

Single-sided p^+n detectors, requiring only one-sided processing, have been shown to perform very well in the LHC radiation environment. If single-sided readout is chosen, p-side readout is preferred due to much simpler truly single-sided technology, lower electric field inhomogeneities and improved fault tolerance in the production process.

Acknowledgements

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